An experimental analysis of thermal storage materials applied to natural-draft condensers

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ABSTRACT

The aim of this work is to study the effect of applying thermal storage materials (TSMs) into natural-draft condensers of household refrigerators. To this end, three types of TSMs were integrated into the wire-and-tube condenser of an appliance. Energy consumption tests were carried out under different system operating conditions with each TSM in order to compare the results with those of an off-the-shelf refrigerator. It was found that the energy consumption benefits are strongly dependent on the contact resistance between the condenser and the material, on the compressor on and off times and on the material thermal capacity, regardless of the ambient temperature. Energy savings of up to 7.4% were achieved with the integration of 700g of a copolymer compound into the condenser of an A++ European appliance.

Keywords: Thermal Storage Material, Refrigerator, Natural-draft Condenser, Energy Consumption.

1. INTRODUCTION

A phase change material (PCM) is a substance with high latent heat of fusion, which is capable of storing and releasing large amounts of energy while changing phase (Bruno *et al.*, 2015). Recently, such materials have been widely used in several applications, such as construction, to increase the thermal inertia of buildings and consequently reduce the costs associated with air conditioning (Cabeza et al., 2011); in preserving food and pharmaceuticals, reducing temperature stratification or prolonging storage time (Phimolsiripol et al., 2008); and as energy regenerators in various applications of thermal systems. Thermal storage materials (TSMs), on the other hand, have a high heat storage capacity without phase changing. Such materials are generally cheaper and might be used for similar applications and purposes. Recent studies showed that the incorporation of PCMs or TSMs into refrigerators can lead to significant performance gains.

Over the past decade, PCM usage into heat exchangers or refrigerated compartments of household refrigerators has grown significantly. According Joybari et al. (2015), most of the studies available in the open literature explore the PCM application in the evaporator or refrigerated compartments. In general, the integration of PCMs into refrigerated compartments or directly into the evaporator causes both a reduction in energy consumption and in the fluctuation of the average temperature of the refrigerated compartment. Moreover, it causes a substantial increase in the time that the refrigerator maintains the temperature at an acceptable level with the compressor off, which brings benefits to the pharmaceutical and food preservation areas or in cases of power outage, for example. Regarding the application of such materials to condensers, most authors reported a significant reduction in the condensing temperature and, consequently, energy consumption.

Cheng et al. (2013) modelled a household refrigerator with integrated PCMs into a natural-draft condenser. The authors state that, under regular conditions without PCM, the condensers operate actively only during the compressor on period. However, the presence of heat storage materials can extend the heat dissipation of the condensers also for the compressor off period. That is, during the compressor on period, a portion of the heat is stored in the material while the other portion is dissipated to the environment. When the compressor shuts off, the heat stored in the material is dissipated. Thus, there is continuous condenser heat dissipation, whether the compressor is on or not. When the heat dissipation occurs during the compressor off period, the heat transfer efficiency is higher, which results in a lower condensing temperature, reducing energy consumption. The

authors further claim that at the beginning of the compressor on period, the PCM temperature is low and the heat storage potential is high, causing a momentary increase of the COP of the system.
Similarly, Sonnenrein et al. (2015a) evaluated the influence of different materials (water, paraffin and a polymer compound) added to a wire-on-tube condenser over the condensing temperature and energy consumption of a household refrigerator. The authors reported a significant decrease in condensing temperature and reductions of up to 10% in energy consumption. Furthermore, Sonnenrein et al. (2015b) also evaluated the performance of a commercial refrigerator equipped with 150g of a copolymer-bound PCM in the evaporator and 500g in the condenser. The authors reported a reduction of up to 8°C in the condensing temperature and up to 7% in energy consumption.
Recently, Rametta (2018) performed experiments with PCMs integrated into a natural-draft wire-on-tube condenser used in a 422-liter frost-free bottom-mount domestic refrigerator. The author investigated the performance of PCMs under different operating conditions. To do so, an external control was developed to vary the compressor on and off periods. At the optimum operating condition, the reduction in energy consumption reached 5.4% with the use of 1.02 kg of water bags between the condenser wires. In this context, the author stated that PCMs should be selected considering the thermal characteristics of the material and the compressor on and off periods.
To the best of the author’s knowledge, there are no studies in the open literature that systematically investigated the effects of the TSMs integration on the performance of domestic refrigerators, considering different compressor on and off periods and thermal load. In this context, the present work aims to investigate the effect of thermal storage materials applied to natural-draft condensers. To this end, three materials were selected, with different thermal properties and attaching method to the condenser, and tests were performed under several operating conditions.

2. EXPERIMENTAL WORK

Tests were conducted with a 144-liter all-refrigerator built-in domestic refrigerator with European A++ energy rating. The refrigerator uses a skin-type evaporator, a reciprocating compressor, which operates with 19g of R600a, and a natural-draft wire-on-tube condenser, which is 505mm high and 522mm wide, with 11 tube passes and 144 wires.
The refrigerator was instrumented with temperature, pressure and power transducers. The discharge and suction pressures were measured with absolute pressure transducers with maximum uncertainty of ±0.01bar. The compartment temperatures were measured with T-type thermocouples, with maximum uncertainty of ±0.2°C, which were brazed in small copper cylinders as recommended by IEC62552 (2013). The compressor power was measured with a power integrator. Energy consumption was calculated with maximum uncertainty of ±5.0kWh/year.
Three types of TSMs were integrated into the condenser, namely: (i) commercial PCM OM37P, (ii) water and (iii) polymeric compound (also called bitumen). The physical characteristics of the materials are detailed in Tab. 1. Small bags of water and organic commercial PCM RT44HC were inserted among the condenser wires. In contrast, the bitumen was adhered to the wires and tubes of the condenser due to its softness and adhesive characteristics. The condenser, PCM and TSMs temperatures were measured with T-type thermocouples installed on the respective surfaces.

Table 1. Thermal storage materials characteristics

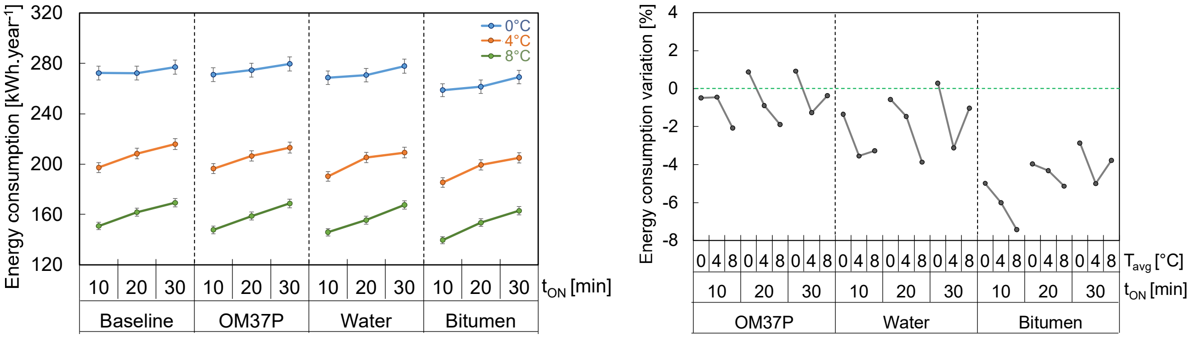
	OM37P	Water	Bitumen
Mass [kg]	0.50	0.51	0.73
Phase change temperature [°C]	37	0	-
Latent heat of fusion [kJ kg^{-1}]	218	333	-
Specific heat [kJ kg^{-1}K^{-1}]	2.0	4.2	1.8
Bag type [-]	aluminum film	aluminum film	-

The performance of the TSMs was evaluated through energy consumption tests based on the requirements of IEC 62552 (2013) standard for built-in refrigerators. All the tests were carried out in a climatic chamber, with controlled ambient temperature and relative humidity. The tests were conducted with different compressor on periods (10, 20 and 30min) and different average compartment temperatures (0, 4 and 8ºC), covering a significant range of compressor run time ratios. The full combination of these variables resulted in 9 tests per material. Considering the baseline tests (without TSM) and the three different types of materials, the full matrix add up to 36 experimental tests, performed at an ambient temperature of 32°C. Additional tests were performed at 16°C ambient temperature, considering only baseline condition and bitumen.

The original control strategy of the refrigerator has been replaced by an external control with direct actuation in the compressor. The new control operates based on average compartment temperature readings. The desired compressor on time and average compartment temperature are obtained in an iterative process by selecting the on and off compartment temperatures.

3. RESULTS

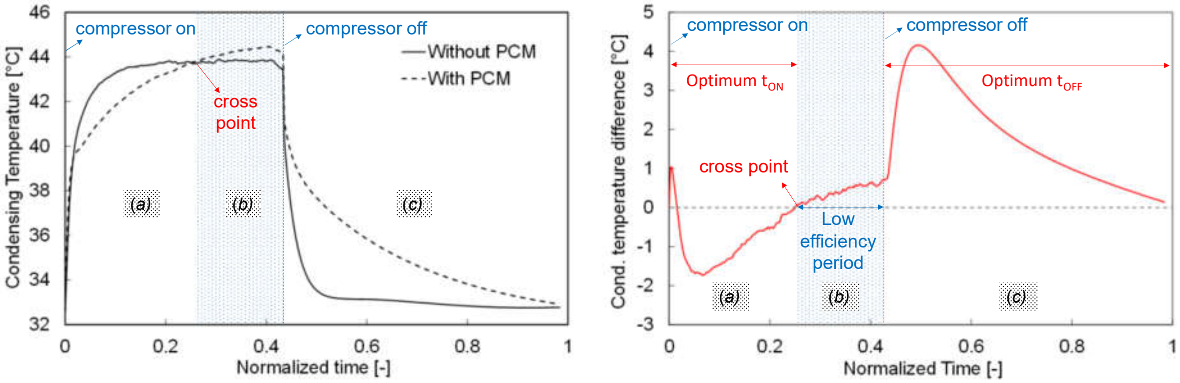
Figure 1(a) shows the energy consumption results for all configurations tested. As expected, lower compartment temperatures lead to higher thermal loads and, consequently, higher energy consumption. Fig.1(a) also shows that, regardless of the material used, the energy consumption decreases with the reduction of the compressor on time. Figure 1(b) shows the variation in energy consumption caused by the integration of the materials in the condenser, when comparing to the baseline case, including different compartment average temperatures and compressor on periods. The use of bitumen in the condenser resulted in an average 4.8% energy saving. In its turn, the water bags caused an average energy consumption reduction of the order of 2.0%. When the commercial PCM OM37P was used, the average reduction was only 0.6%. Note that generally the energy savings are higher for higher compartment average temperatures, i.e., for lower compressor run time ratios. In addition, reduced compressor on times (10min) also present higher energy savings. The maximum energy consumption reduction (7.4%) was achieved with the highest compartment average temperature (8°C) and the lowest compressor on time (10 minutes).



(a) (b)

Figure 1: Energy consumption results for all materials and configurations tested

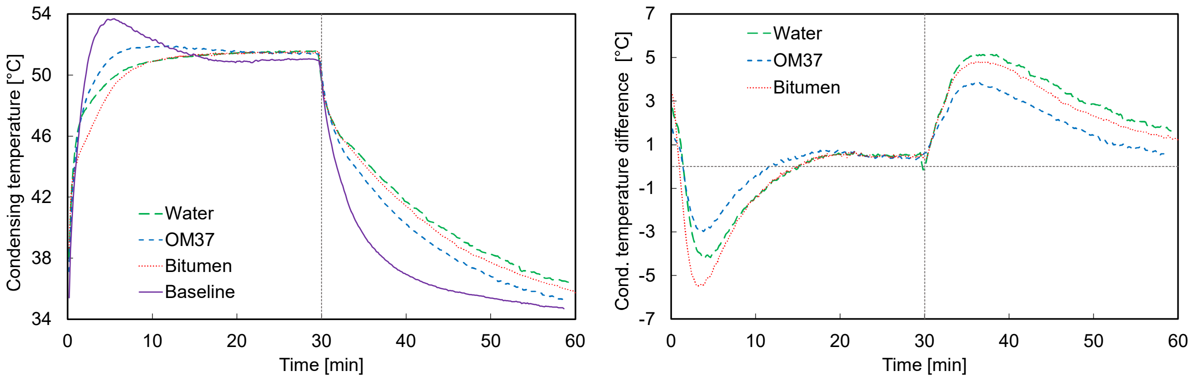
The energy savings caused by the integration of the materials can be explained by the behavior of the system during a complete compressor cycle. Fig. 2(a) shows typical condensing temperatures, for a normalized cycle, of a system with and without PCM. Additionally, Fig. 2(b) shows the difference between both temperatures plotted in Fig. 2(a) ($T_{cond,PCM}$ - T_{cond}). During the beginning of the compressor on period, the heat transfer between the condenser and the PCM is higher due to the high temperature difference, which results in a temporary reduction of the condensing temperature. Therefore, it is noted that the temperature difference shown in Fig. 2(b) is negative (region a), which represents benefits to the system. However, after a certain time, the PCM temperature rises and the condensing temperature curves intersect at the point where the condensing temperature with PCM exceeds the baseline configuration. From this point forward, called cross-point, the heat transfer between the condenser and the PCM is lower, which negatively affects the condensing temperature of the system with PCM (region b). Such behavior clearly indicates that there is a maximum compressor on time that maximizes the system performance with PCM. When the compressor shuts off, the condenser temperature reduction during this period is much slower with the presence of the PCM (region c) due to the thermal inertia of the material. If the compressor is switched on early, the condenser temperature at the beginning of the next cycle will still be high, with negative effects on system performance. It means that there is also a minimum compressor off period that maximizes the system performance with PCM.



(a) (b)

Figure 2: (a) Condensing temperatures and (b) condensing temperatures difference during an on-off cycle of a system with and without PCM

Fig. 3(a) shows the condensing temperatures during a complete cycle for all materials tested, with 4°C compartment average temperature and 30min compressor on time. In addition, Fig. 3(b) shows the difference of the condensing temperatures with and without TSMs, for the same test conditions. It is noted that the condensing temperature at the beginning of the compressor on time is reduced by the presence of the TSM, reaching the cross-point, and later reducing slowly the temperature during the compressor off time, due to the thermal inertia of the material. These results showed that the beneficial effects of the TSM are proportional to the difference between the condensing temperature curves with and without TSM at the beginning of the compressor on period (see Fig. 3b). The lower the condensing temperature at the beginning of the cycle, the better the system energy performance.



(a) (b)

Figure 3: (a) Condensing temperatures and (b) condensing temperatures difference during an on-off cycle of the test with 4°C compartment average temperature and 30min compressor on period

Fig. 4 shows the condensing temperatures difference of the system with and without bitumen, for the compartment average temperature of 0°C, 4°C and 8°C and compressor on periods of 10min, 20min and 30min (Figures 4a, 4b and 4c, respectively). In these cases, the average compressor run time ratio were 64% (0°C), 46% (4°C) and 35% (8°C), respectively. For higher run time ratios (black lines), the compressor off period is not long enough to provide appropriated condenser temperature reduction at the end of this period, adversely affecting the condensing temperature at the beginning of the next cycle. Note that the attenuation at the condensing temperature at the beginning of the cycle is lower for this condition. As the compressor operating fraction is reduced (blue and red lines), the compressor off period becomes long enough to allow a higher heat rejection of the TSM and hence the condenser. In this case, the condensing temperature at the beginning of the next cycle is lower due to the higher heat transfer rate. Therefore, it can be concluded that the lower the compressor run time ratio, the greater the system performance with TSM. In fact, the results show higher energy savings for higher compartment average temperatures. All other materials presented similar behavior to bitumen.

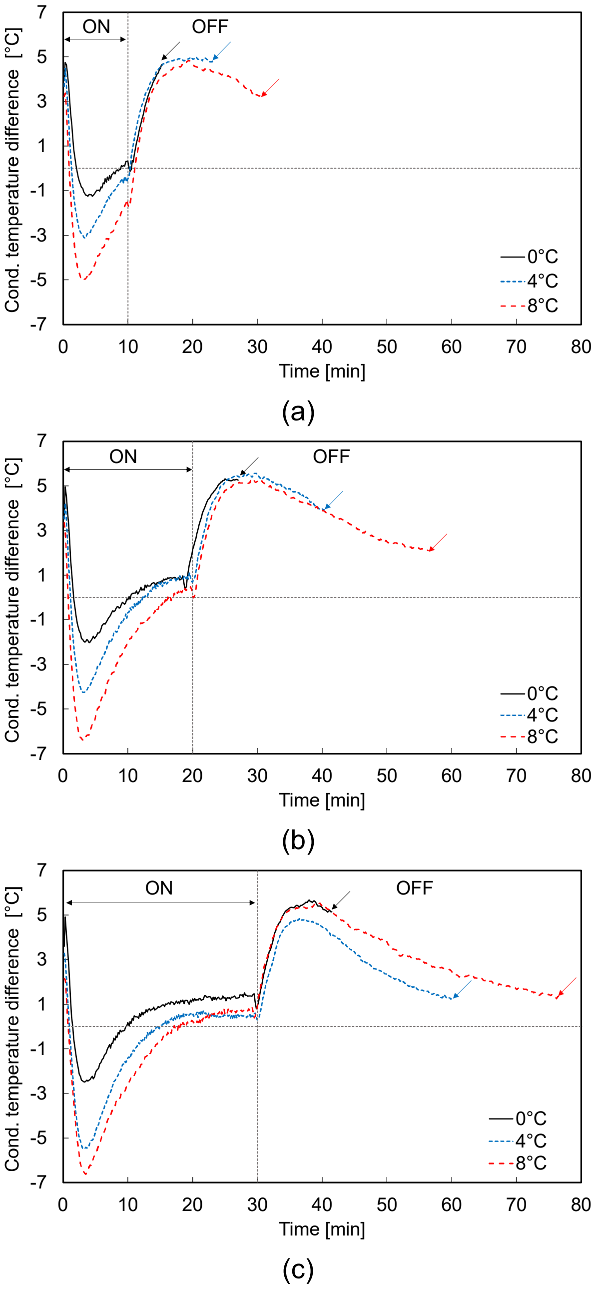


Figure 4: Condensing temperatures difference with and without bitumen during an on-off cycle of the tests with (a) 10min, (b) 20min and (c) 30min compressor on period

When the compressor on time is short (Fig. 4a), the condensing temperature with TSM remains always lower than the condensing temperature of the baseline condition, that is, the temperature difference is always negative during the whole compressor on period, meaning that the cross-point is not reached. On the other hand, as the compressor keeps on for longer periods (figures 4b and 4c), the cross-point is reached, provoking an inefficient operating condition, since the material starts to act as a thermal resistance in the condenser. In short, the lower the compressor on time, the higher the energy savings.

Moreover, the results indicate that systems which operate with high compressor run time ratio (i.e. low compartment temperature or low compressor capacity) reach the cross-point earlier, due to the reduced compressor off time that harms the condenser temperature reduction during the off period. In contrast, systems that operate with short compressor on time avoid or shorten the cross-point reaching. In other words, the lower the run time ratio and the shorter the compressor on period, the higher the energy savings of TSM equipped systems. Therefore, it can be concluded that there is a maximum compressor on time and a minimum compressor off time that optimizes the performance of the system with TSM. Such periods are dependent on the characteristics of the system and the material, since they depend on the heat rejection rate of the condenser during the compressor on and off cycles, which in turn is a function of the size of the condenser as well as the thermal capacity and attaching method of the TSM with the condenser.

The heat transfer process in natural-draft condensers is dominated by convection, which represents 65% of the total heat exchanged, being the rest rejected to the environment through radiation (Bansal and Chin, 2003). When the TSM is integrated into the condenser, a portion of the heat exchanged occurs through conduction between the material and the tubes and wires. If the contact resistance between the condenser and the material is low, the conduction process becomes dominant, since the conduction thermal resistance is lower when compared to the convection and radiation processes. This phenomenon is most pronounced at the beginning of the cycle, when the TSM is at a lower temperature. As the TSM absorbs heat from the condenser, its temperature increases and the heat transfer by conduction becomes no longer significant (this effect might be delayed for materials with higher thermal capacities). At this moment, depending on the attaching method between the material and the condenser, the presence of TSM may hinder the convection heat transfer, since it can act as a thermal insulation and even change the flow pattern of natural convection, reducing turbulence effects. Therefore, the lower the contact resistance and the greater the thermal capacity, the better the system performance.

In this context, considering the characteristics of each material used in the present work, the thermal capacity of the commercial PCM OM37P was estimated at 12.8 kJK^{-1}, bitumen at 13.9 kJK^{-1} and water at 22.1 kJK^{-1}. Among the materials that presented benefits to the system, bitumen was the most significant (-4.8%), followed by water (-2.0%) and commercial PCM OM37P (-0.6%). Note that there is no direct correlation between the thermal capacity and energy savings, indicating that the material selection should not only consider the thermal capacity. As a matter of clarification, Fig. 5 shows the attachment between the condenser and the (a) bitumen and (b) water bags. Bitumen is a flexible adhesive material that adheres very well to the tubes and wires, minimizing the contact resistance. On the other hand, water bags and commercial PCM were manually placed between the condenser wires, resulting in a significantly higher contact resistance. That is why the bitumen presented a better performance even with a lower thermal capacity.


(a) (b)

Figure 5: Condenser attachment with (a) bitumen and (b) water bags

Fig. 6 shows thermographs of the condenser with bitumen obtained with an infrared camera at three instants of a typical cycle: (i) immediately before the compressor turns on, (ii) in the middle of the compressor on time and (iii) just before the compressor shuts off. These images were obtained in tests with 4°C compartment average temperature and 10min, 20min and 30min compressor on periods. The images show that, for longer periods of compressor on (20 and 30min), the condenser temperature in the middle of the cycle is already high and it is close to the temperature at the end of the cycle. As already mentioned, the heat transfer between the condenser and the TSM decreases until it reaches the cross-point, where it has a negative effect on the condensing temperature, i.e., the heat transfer process at the end of the compressor on period becomes efficient. In other words, shorter is the compressor on period, higher is the benefits. The images also show that, for short compressor on time (10min), the condensing temperature at the compressor start-up is adversely affected. Despite such drawback, the benefits on not reaching the cross-point due to the low off period is higher.

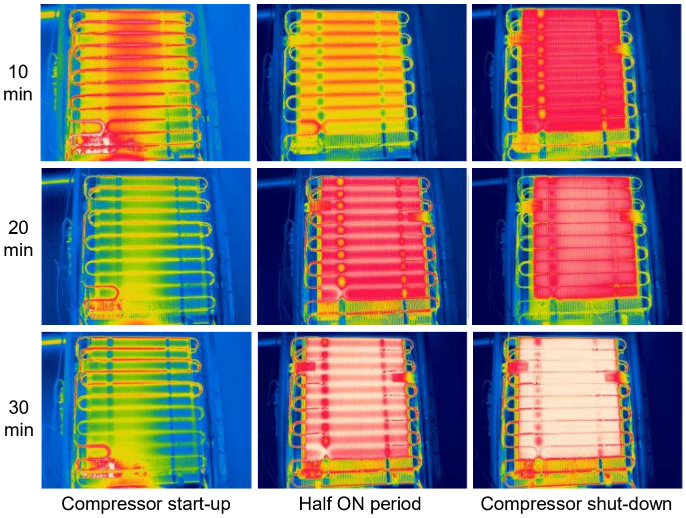


Figure 6: Condenser temperatures with bitumen integrated in the tests with 4°C compartment average temperature and 10, 20 and 30min compressor on time

Finally, the energy consumption tests were also performed at a 16°C ambient temperature. Thus, eighteen additional tests were conducted without TSM and with bitumen into the condenser. It was noted that the energy consumption reduction at 16°C is of the same order of magnitude of the reduction observed at 32°C, which indicates that the performance improvement by the integration of the material into the condenser is not dependent on the ambient temperature.

4. CONCLUSIONS

The present study investigated the effect of the use of thermal storage materials on natural-draft condensers in a A++ European household refrigerator. To this end, three types of TSMs were integrated into the condenser: (i) commercial PCM OM37P, (ii) water and (iii) a polymeric compound. The performance of the TSMs was evaluated through energy consumption tests with different compressor on periods (10, 20 and 30min) and different compartment average temperatures (0, 4 and 8ºC), comprising a significant range of compressor run time ratios.

Considering all operating conditions tested at 32°C ambient temperature, the use of 700g of bitumen into the condenser resulted in an average energy saving of 4.8%. When water capsules and the commercial PCM OM37P were used, the average reduction was of the order of 2.0% and 0.6%, respectively. Energy consumption tests at 16°C ambient temperature were also performed with bitumen integrated into the condenser and the results indicated that the energy savings due to the integration of TSM is not related to the ambient temperature.

It was noted that the energy savings are higher for lower compressor run time ratio and lower compressor on times. Indeed, in the present work, the maximum energy consumption reduction (7.4%) was achieved with the highest compartment average temperature (8°C) and the lowest compressor on time (10min). When the compressor on time is too long, at a given cross-point the condensing temperature with TSM exceeds the condensing temperature without TSM, then the material acts as a thermal resistance and the condenser starts to operate at an inefficient condition. The results also showed that the contact resistance between the material and the condenser play a role as important as the thermal capacity of the material. That is, the material must be selected and attached seeking to minimize the contact resistance. Finally, it was concluded that there is a maximum compressor on time and a minimum compressor off time that optimizes the system performance. Such periods are dependent on the condenser size, TSM attaching method and material thermal capacity.

ACKNOWLEDGEMENTS

This study was made possible through the financial investment from the EMBRAPII Program (POLO/UFSC EMBRAPII Unit - Emerging Technologies in Cooling and Thermophysics). The authors thank Embraco S.A. for financial and technical support.

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